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High-power non linear frequency converted laser diodes

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ABSTRACT

We present different methods of generating light in the blue-green spectral range by nonlinear frequency conversion of tapered diode lasers achieving state-of-the-art power levels. In the blue spectral range, we show results using single-pass second harmonic generation (SHG) as well as cavity enhanced sum frequency generation (SFG) with watt-level output powers. SHG and SFG are also demonstrated in the green spectral range as a viable method to generate up to 4 W output power with high efficiency using different configurations.

Keywords: tapered diode laser, second harmonic generation, sum frequency generation, visible lasers

1. INTRODUCTION

Many applications, e.g., within biophotonics require laser sources in the blue-green spectral range¹. A preferred method for such lasers has been frequency doubled solid state lasers. Such technology tends to be bulky and expensive and therefore alternatives are desired. Diode lasers in the blue-green spectral range have emerged recently but still, the power level for diffraction limited light is limited to about 100 mW^{2,3}. High power diode lasers are available in the near-infrared spectral range but these broad area diode lasers cannot efficiently be frequency converted to the visible spectral range.

Tapered diode lasers are an established method to generate high power in a near-diffraction limited beam at wavelengths ranging from red to infrared⁴. More than 10 W of output power in a near-diffraction limited beam has been demonstrated at wavelengths between 920 nm and 1064 nm^{5,6}. Furthermore, the use of integrated Bragg gratings in such diode lasers enables narrow spectrum emission. Nonlinear frequency conversion of tapered diode lasers is an efficient method for generation of coherent light in the required blue-green spectral range^{7,8}.

SHG of tapered diode lasers has been demonstrated at many different wavelengths and power levels⁹⁻¹². Here we present the generation of up to 2.7 W by single-pass SHG of a single tapered diode laser. Methods for increasing this power level including SFG and cascaded SHG are shown to enable generation of up to 4 W at 532 nm in a near-diffraction limited beam. These power levels are state-of-the-art for nonlinear frequency converted diode laser systems. In addition, a method of generating visible light using SFG between a coupled cavity tapered diode laser and an external cavity tapered diode laser is also presented.

Such frequency converted laser systems are used as pump sources for Ti:sapphire lasers and examples of their use within biophotonics imaging are presented. The low noise of the diode laser sources provides enhanced image contrasts, which is important for diagnostics.

2. SECOND HARMONIC GENERATION

2.1 Experimental setup

Tapered diode lasers are a special kind of diode lasers consisting of a single-mode ridge section and a tapered amplifier section¹³. The single-mode section provides good beam quality and the tapered section amplifies the output from the single-mode section yielding a high output power. The opening angle of the tapered amplifier section is chosen to suit the diffraction angle of the beam exiting the single-mode ridge section. For wavelength control, different Bragg grating structures may be integrated in the single-mode section. A sketch of a tapered diode laser is shown in Figure 1.

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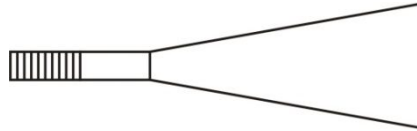


Figure 1. Sketch of a tapered diode laser. In the ridge section a Bragg grating can be included for frequency selectivity.

Single-pass SHG is the simplest way of converting near-infrared light to visible light. A sketch of the setup is shown in Figure 2. Light from the tapered diode laser is collimated in both the fast and slow axes using a combination of an aspherical lens and a cylindrical lens. A proper choice of these lenses can lead to an almost circular beam without astigmatism. Astigmatism is a challenge when using tapered diode lasers as the astigmatism depends on both the operating power and the length of the tapered section.

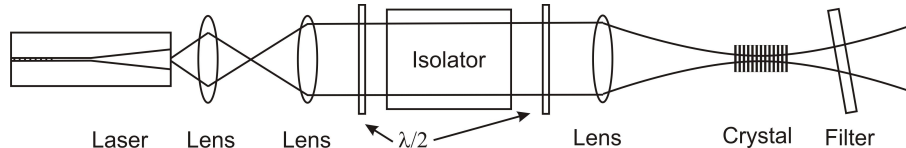


Figure 2. Sketch of a typical experimental setup for single-pass SHG of a tapered diode laser.

An optical isolator is typically used to protect the tapered diode laser from optical feedback as this can cause the laser to become unstable or even permanently damage the laser. Using a half wave plate in front of the isolator enables variation of the input power to the nonlinear crystal without changing the operating conditions and thus the astigmatism of the tapered diode laser. The light is focused inside the nonlinear crystal in order to optimize the conversion efficiency according to Boyd and Kleinman¹⁴. After the crystal, the remaining infrared light is filtered away and the frequency converted beam may be collimated to ease integration in applications.

2.2 Generation of 532 nm light

In the green wavelength range, 532 nm is the wavelength of most commercial solid state lasers based on the 1064 nm transition in Nd:YAG or Nd:YVO₄. Tapered diode lasers emitting at 1064 nm have been demonstrated with power levels above 12 W and with excellent spectral and spatial properties⁶. Single-pass frequency doubling of such lasers in 30 mm long PPMgLN crystals have previously been shown to generate more than 1.5 W of output power in a near-diffraction limited beam¹⁵. Here we have optimized the setup and have achieved up to 2.72 W of output power using a 50 mm long PPMgLN crystal in a setup similar to Figure 2. The 6 mm long DBR tapered diode laser was similar to the ones demonstrated in^{4,6,15}. The light emitted by the laser was collimated in the fast axis using an 8 mm focal length aspherical lens and a cylindrical lens with 80 mm focal length was used to collimate the light in the slow axis and compensate for the astigmatism. After passing an optical isolator and two half wave plates, the light was focused inside the 50 mm long periodically poled MgO-doped LiNbO₃ (PPMgLN) crystal (HC Photonics). The crystal was poled with a period of 6.92 μm, anti-reflection coated on both facets at both the fundamental and second harmonic wavelengths and temperature stabilized in an oven to approximately 40°C. The laser was operated at a temperature of 20°C and with currents to the ridge section and taper section of 350 mA and 16 A, respectively. The measured power characteristics of the SHG experiment is shown in Figure 3. The experimental results are fitted to the theoretical curve for SHG with pump depletion using the relation

$$P_{SHG} = P_{laser} \tanh^2(\sqrt{\eta_{SHG} P_{laser}}) \quad (1)$$

Here η_{SHG} is the nonlinear conversion efficiency and P_{laser} is the fundamental laser power. The fit gives a nonlinear conversion efficiency of $\eta_{SHG} = 3.6 \text{ \%}/\text{W}$. The power conversion efficiency in the SHG experiment is 28.4 %.

The SHG beam is close to being diffraction limited with a beam quality of $M^2 < 1.3$ and the spectral linewidth of the green light is smaller than 2 pm, limited by the resolution of the optical spectrum analyzer (Advantest Q8347).

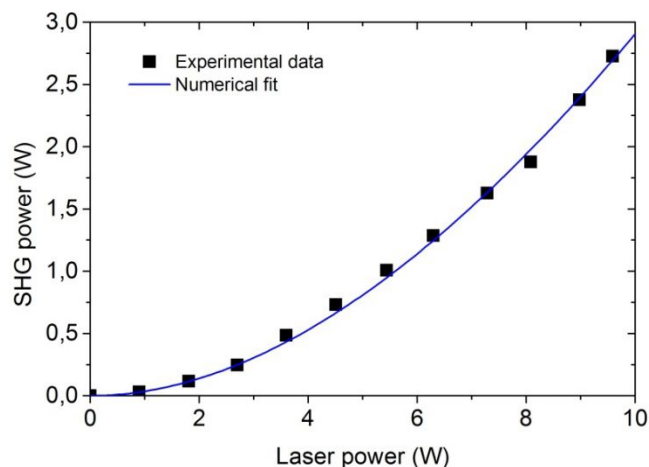


Figure 3. Measured SHG output power vs. fundamental input power. The squares are measured values and the solid curve is a fit to the experimental values using the depleted pump approximation in (1).

Such frequency doubled tapered diode lasers have been built into compact and robust laser modules. Using a 30 mm long PPMgLN crystal, up to 2.3 W of output power at 532 nm has been obtained. Using photodiode feedback, the output power can be stabilized to within $\pm 0.2\%$ over extended periods of operation. An example of such a compact laser module emitting green light at 532 nm is shown in Figure 4.

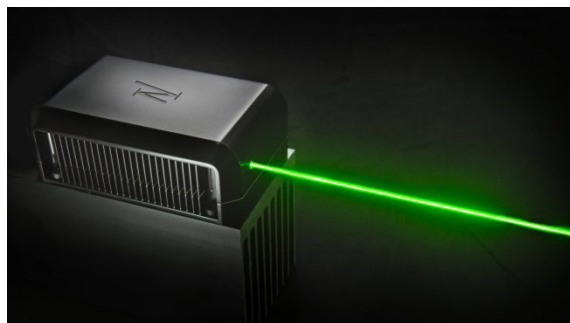


Figure 4. Compact laser module emitting more than 2 W of green light at 532 nm (Photo courtesy of Henrik Petit).

Using this simple technology, many wavelengths in the visible spectral range can be reached. Tapered diode lasers are available at many wavelengths in the near-infrared spectral region and frequency doubling of these lasers enables generation of light throughout the visible spectral region. High power has been generated at blue wavelengths at for example 460 nm and 488 nm and recently we have also demonstrated high output power at 515 nm. Tuning of tapered lasers is possible by different means and large tuning ranges can be reached^{16–18}. In this way tunable visible radiation can be obtained.

2.3 Cascaded SHG setup

In order to increase the second harmonic output power and conversion efficiency available from a single tapered diode laser, different possibilities exist. One approach is to resonate the laser beam in an enhancement cavity containing the nonlinear crystal and in this way increase the efficiency¹⁹. The complexity of this approach is, however, significant as the cavity must be held resonant with the laser frequency. A second possibility is to have multiple passes in the nonlinear crystal²⁰. At the power levels used in this work, heating due to absorption in the nonlinear crystal limits the efficiency as the phase matching set-point temperature for two different passes will be different. A third approach, which we exploit here, is to use a cascade of nonlinear crystals²¹. A sketch of the setup is shown in Figure 5. Both the fundamental and second harmonic light exiting the first nonlinear crystal is re-focused into the second nonlinear crystal. In this way, it is possible to increase the efficiency by a factor of 4 assuming no depletion of the fundamental beam. Dispersion between the fundamental and second harmonic beams necessitates compensation of the relative phase at the input to the second

nonlinear crystal in order for the generated green light to add constructively. Here we used a plane glass plate to compensate the dispersion.

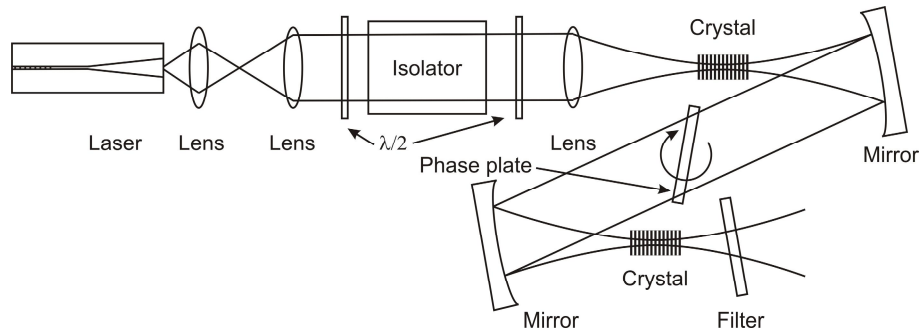


Figure 5. Schematic of the setup for cascaded SHG of a tapered diode laser using two nonlinear crystals.

Using two 30 mm long PPMgLN crystals, we have generated up to 3.5 W of light at 532 nm from 10 W of input power from the DBR tapered diode laser⁷. This corresponds to a factor of 2.3 more than the second harmonic power obtained from either only the first nonlinear crystal or only the second nonlinear crystal.

3. SUM FREQUENCY GENERATION

3.1 Single-pass SFG setup

In SFG the beams from two different lasers are combined and focused into a nonlinear crystal to efficiently generate a beam at the sum frequency of the two input beams. The two different lasers beams can be combined in different ways, depending on the spectral difference between the two fundamental laser beams. If the two beams have a large wavelength separation, a dichroic mirror can be used to combine the two beams. If the two lasers are closely spaced spectrally, different means than a dichroic mirror have to be used, for example a volume Bragg grating. A generic sketch of a setup for single-pass SFG with a dichroic mirror used as beam combiner is shown in Figure 6.

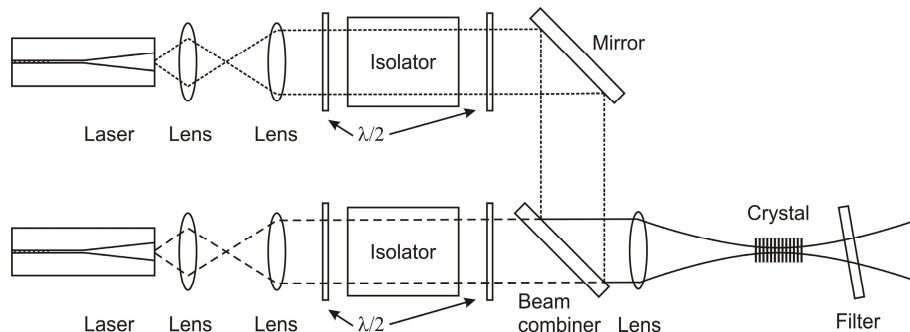


Figure 6. Sketch of experimental setup for SFG between two tapered diode lasers.

If the wavelength separation is large, two different optical isolators must be used, while a single isolator is sufficient if the lasers are within the acceptance bandwidth of the optical isolator. By combining a proper combination of tapered diode lasers, a large span of wavelengths may be reached.

3.2 Generation of 509 nm light

An experimental demonstration of SFG between two different tapered diode lasers was carried out using DBR tapered diode lasers at 978 nm and 1063 nm, respectively²². Both lasers were collimated in the fast and slow axes using a combination of an aspherical lens and a cylindrical lens. After passing a combination of half wave plates and an optical isolator, the lasers were combined using a dichroic mirror. A lens focused the combined beams to a beam radius of approximately 35 μm in the 20 mm long PPMgLN crystal (Covesion) and a filter was used to separate the generated beam at 509 nm from the two fundamental beams. We used a poling period in the PPMgLN crystal of 6.03 μm and the crystal was temperature stabilized at 62.95°C for optimum phase matching. Using this setup, up to 1.73 W of output power was generated at a center wavelength of 509.64 nm. The power characteristics are shown in Figure 7.

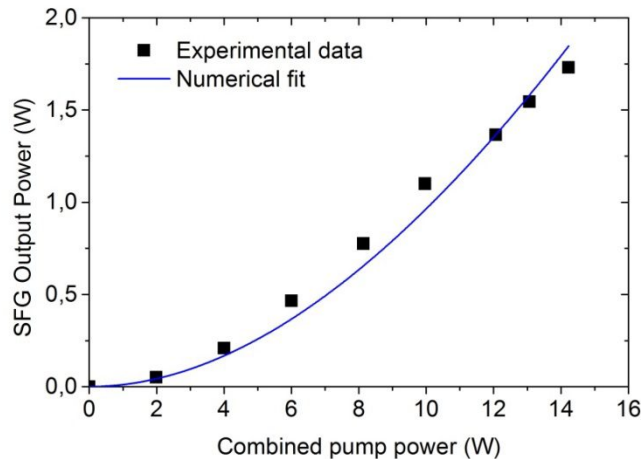


Figure 7. Measured output power at 509 nm vs. combined pump power. The squares illustrate the measured power values and the solid curve is a numerical fit to the experimental results using the depleted pump approximation in (1).

The 509 nm light was nearly diffraction limited with measured M^2 values of 1.1 in both the fast and the slow axes. The spectral linewidth of the 509 nm light was below 2 pm limited by the resolution of the optical spectrum analyzer.

3.3 Generation of 532 nm light

Sum frequency generation between two nearly identical lasers was demonstrated by combining two 1063 nm DBR tapered lasers in a volume Bragg grating (VBG) and mixing the combined beam in a nonlinear crystal²³. The two lasers were temperature tuned to have a 1 nm wavelength separation to allow for efficient combination in the VBG. The wavelength of the laser diffracted in the VBG must be chosen carefully to fit with the VBG characteristics and the incidence angle on the VBG. After collimation, the lasers were combined and the combined beam was sent through a combination of half wave plates and an optical isolator before being focused into a temperature stabilized 30 mm long PPMgLN crystal. Up to 3.9 W of output power at 531.5 nm was generated as shown in Figure 8. This corresponds to a 2.5 times increase in output power compared to SHG of a single laser. At low power a 3.2 times increase was observed. In theory, an increase by a factor of 4 could be expected at low power without pump depletion. The discrepancy can be explained by the non-ideal beam properties of the tapered diode.

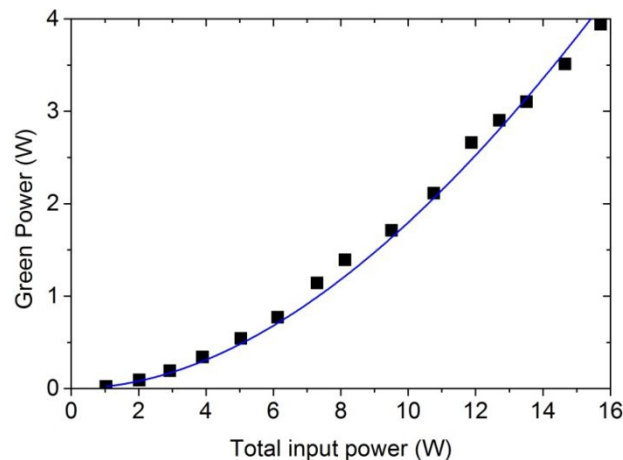


Figure 8. Measured green output power from SFG between two DBR tapered diode lasers at 1063 nm. The squares are the experimentally obtained values and the solid curve is a numerical fit to the experimental values using the depleted pump approximation in (1).

The generated light was nearly diffraction limited with measured M^2 values of <1.1 in the fast axis and <1.3 in the slow axis. The linewidth of the 532 nm light was below 2 pm limited by the resolution of the optical spectrum analyzer.

3.4 Cavity enhanced SFG

A different approach for the generation of visible light by SFG between two tapered diode lasers is to use a coupled ring cavity as in the sketch shown in Figure 9²⁴. One tapered amplifier is operated in a unidirectional ring cavity which is coupled to a bow-tie enhancement cavity. This tapered amplifier operates at a single frequency dictated by the enhancement cavity resonance and the diffraction grating. The light circulating in this coupled ring cavity is automatically filtered spatially to a pure Gaussian beam due to the enhancement cavity. The circulating power in the enhancement cavity is significantly higher than the output power from the tapered amplifier and the nonlinear crystal is positioned in this cavity to take advantage of the high circulating power. A beam from an external cavity tapered diode laser is single-passed through the nonlinear crystal to generate light at the sum frequency. The generated light has a significantly better beam quality than the light emitted from the external cavity tapered diode laser due to nonlinear beam clean-up in the SFG process with the Gaussian beam inside the nonlinear crystal²⁵.

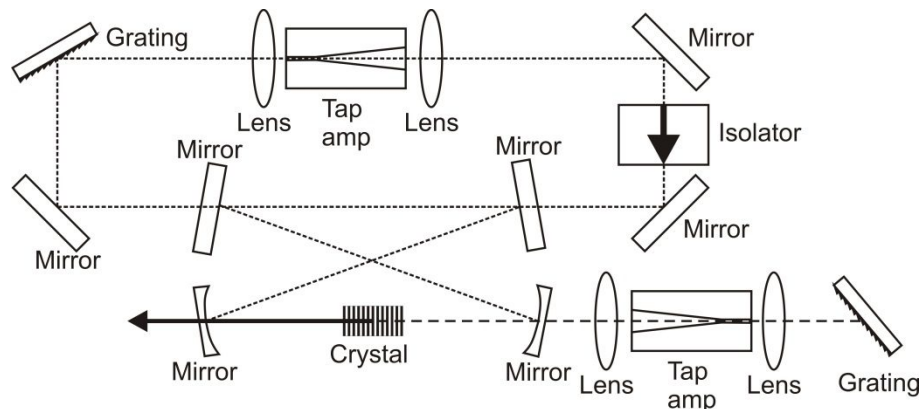


Figure 9. Simplified experimental setup for coupled ring cavity SFG between two tapered diode lasers.

Using a tapered amplifier with a center wavelength of 1060 nm in the coupled ring cavity and an 808 nm external cavity tapered laser, we have extracted 340 mW of blue light at 459 nm as shown in Figure 10. Also shown in Figure 10 is the circulating power inside the enhancement cavity. The circulating power is seen to drop when the input power at 808 nm is increased. At increased 808 nm input power, the losses from the SFG increases thus limiting the circulating power. The 459 nm light is nearly diffraction limited with $M^2 < 1.15$ and the light is single-frequency with a linewidth below 20 MHz.

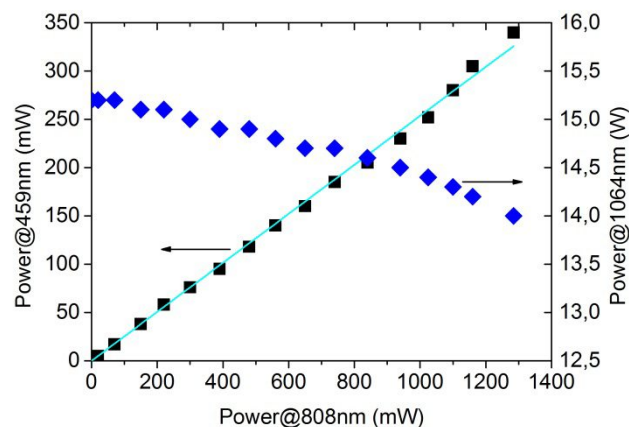


Figure 10. 459 nm output power vs. input power at 808 nm (squares). Also shown is the circulating power in the enhancement cavity (diamonds).

The 459 nm light can be tuned by 1.5 nm limited by the nonlinear crystal. A different choice of nonlinear crystal can extend the tuning range to approximately 17 nm for this particular choice of tapered amplifiers. Selecting different

tapered amplifiers can extend the wavelength coverage to cover most of the visible wavelength range. A similar approach has been demonstrated for SHG of a single tapered laser in a coupled ring cavity^{26,27}.

4. APPLICATIONS

4.1 Ti:sapphire pumping

Such frequency converted high power tapered diode laser as described above have great application potentials, for instance for pumping of Ti:sapphire lasers. Ti:sapphire lasers are typically pumped by frequency doubled solid state lasers. These lasers tend to increase the dimensions and cost of Ti:sapphire laser systems. We have used different frequency converted tapered diode lasers at 509 nm and 531 nm to pump Ti:sapphire lasers and have obtained mode-locked operation with more than 180 mW output power and spectral widths of up to 184 nm (FWHM) as shown in Figure 11^{22,28}. The pulse widths obtained have been shorter than 10 fs.

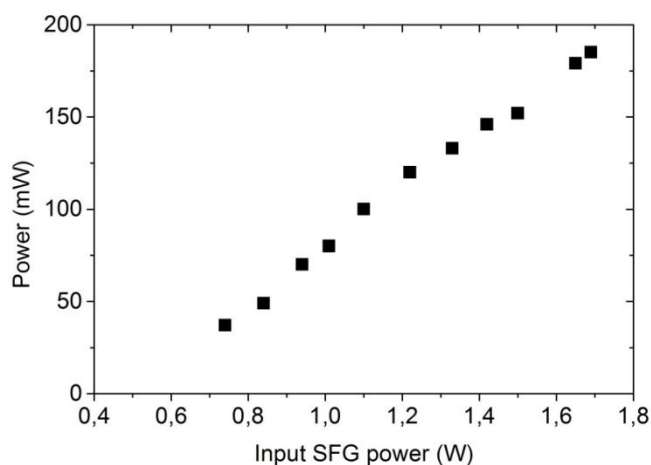


Figure 11. Mode-locked output power vs. input power at 509 nm from a Ti:sapphire laser.

4.2 Optical coherence tomography

Broadband light sources such as ultrafast Ti:sapphire lasers have shown great potential for biophotonic applications like optical coherence tomography (OCT). We have used a Ti:sapphire laser pumped by a frequency doubled tapered diode laser for retinal OCT²⁹. The OCT system was a modified Spectralis OCT device (Heidelberg-Engineering) with built-in fixation target and eye-tracking device. The mode-locked Ti:sapphire laser was modified to emit light with a spectral width of 90 nm (FWHM). Only 0.8 mW was used for the retinal OCT, well below the safety limits. Example OCT tomograms of the retina is shown in Figure 12. The high axial resolution and good contrast in the OCT images illustrate the potential of using frequency converted tapered diode lasers for biophotonics imaging.

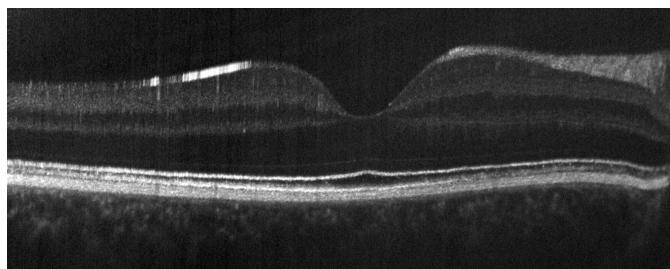


Figure 12. Measured OCT tomogram of the retina using a Ti:sapphire laser pumped by a frequency doubled tapered diode laser.

5. CONCLUSION

Nonlinear frequency conversion of tapered diode lasers enables generation of several watts of power in the visible spectral region. We have shown state-of-the-art power levels for nonlinear frequency converted diode lasers. With single-pass SHG, we have generated up to 2.7 W of output power. Scaling this power level towards 4 W has been demonstrated with cascaded SHG of a single tapered diode laser and SFG between two tapered diode lasers. The excellent beam properties and narrow spectral emission enable use of such lasers in demanding applications such as pumping of Ti:sapphire lasers. Such lasers have proven excellent performance in biophotonic imaging.

The use of tapered diode lasers combined with nonlinear frequency conversion allows generation of light throughout the visible spectral range. In this way, the laser emission may be chosen to fit the desired wavelength optimal for the application.

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